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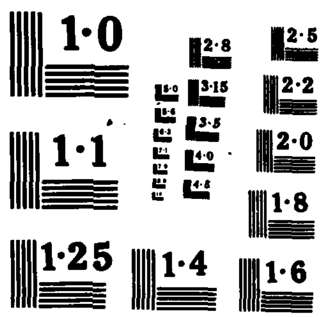
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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

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CRYOGENIC TEST TECHNOLOGY 1984

by

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SUMMARY

This report reviews the new information available on cryogenic test technology since the report of the Conveners' Group on Cryogenic Test Technology was written in 1981 and summarizes the present position.

INTRODUCTION

This report is intended to review the status of cryogenic test technology based on information which has become available since the report[1] of the Conveners' Group which was completed in 1981. That report was comprehensive in scope and didactic in style: therefore to avoid unnecessary repetition this report will concentrate on recent developments. It will be assumed that even if the reader is not familiar with the background it is readily available. In retrospect the Conveners' report seems to have stood the test of time and any revisions today would only be a matter of emphasis.

The major events since the Conveners' report have been the completion and commissioning of the National Transonic Facility (NTF)[2], the suspension of further work on the Douglas 4-CWT blowdown tunnel, the conversion of ONERA T2[3] for cryogenic operation, the steady progress with the DFVLR KKK[4], and the slow but positive progress with the ETW project[5,6], including installation of the pilot tunnel PETW.

In the realm of cryogenic test technology there have been three major collections[7,8,9] of papers which have represented ~~significant~~ additions to the available literature. These have resulted ~~from~~ workshops arranged by NASA Langley in USA and from an ~~information meeting~~ arranged by the ETW project in Europe.

In addition there has been a recent AGARD Fluid Dynamics Panel Symposium[10] on Wind Tunnels and Testing Techniques at Çesme, Turkey which produced several new papers of interest. Also, a meeting of specialists on cryogenic wind tunnel strain gauge balance technology was arranged by ETW in conjunction with ONERA at the Modane Test Centre. Although there were no published proceedings this meeting provided a rare opportunity for discussion among workers in this field.

It should be noted that ~~the various meetings, in addition~~ to providing opportunities for discussion between specialists on aspects of testing in cryogenic wind tunnels, performed the necessary function of educating prospective users of such wind tunnels to their characteristics and, in particular, how testing in them will differ from testing in conventional tunnels.

Additional keywords: //ATO furnished; materials; instrumentation; //flow visualization; laser velocimetry.

~~CRYOGENIC WIND TUNNEL PROJECTS~~

The status of the main cryogenic wind tunnel projects in USA and Europe are briefly summarized in order to place the rest of the paper in context.

The main event has been the completion[2] in September 1982 of the National Transonic Facility (NTF) at NASA Langley Research Center. The checkout of all of its systems took about a year and was finished in September 1983. Aspects of this checkout and some preliminary performance results are discussed in reference 11. Detailed aerodynamic calibration was begun in late 1983 and is expected to take until the last quarter of 1984. The first phase (Figure 1) of the calibration will cover those items usually considered as basic tunnel characteristics (steady-state measurements of Mach number, pressure and temperature in the test section, component load verification, fan performance, test-section variable geometry settings, control responses and repeatability with temperature cycling). The second phase (Figure 2), will cover items more directly associated with data accuracy such as flow quality, wall interference effects, comparisons with other tunnels and with flight results (Boeing 767 and Shuttle Orbiter). This phase of activity is more fully discussed in references 12 and 13.

A considerable amount of information relevant to the design and construction of NTF and its systems has appeared in reference 7 (which although it is dated 1980 was not generally released until 1 July 1982) and reference 8 (Figures 3,4).

The other cryogenic tunnel at NASA Langley, the 0.3 m TCT, has continued operation with a variety of work including two-dimensional aerofoil testing[14,15], experiments on an adaptive wall test section and on optical equipment[16]. Two reports of interest to tunnel operation have been published, one on cooldown strategies[17] and another on safety[18]. In addition preliminary measurements with hot wires of velocity, density and total temperature fluctations in the test-section have been reported[19].

Work on the Douglas Four-Foot cryogenic blowdown tunnel (4-CWT) has been suspended but the One-Foot tunnel (1-CWT) has been used for research investigations[20].

In France the ONERA/CERT transonic induced flow tunnel T2[3,9(15),9(17),9(18),21] (Figure 5) is now adapted for cryogenic operation by application of thin internal insulation. Initial cryogenic runs were made in September 1981. The tunnel has also been fitted with computer-controlled two-dimensional adaptive walls (Figure 6) which have been employed in tests on two-dimensional aerofoils. The flow characteristics (temperature gradients, fluctuations of temperature and pressure, low temperature operating limits) have been examined as well as such matters of interest as transition fixing and wall/flow temperature ratio.

The construction phase of the cryogenic wind tunnel KKK[4,9(24)] at DFVLR, Cologne (Figures 7, 8) converted from an existing atmospheric-pressure concrete low-speed tunnel is proceeding and will be finished early in 1985 to be followed by commissioning and calibration. The specially-developed internal insulation of total thickness 0.35 m is covered with 18 mm wooden panels. The temperature-conditioning chamber for models has already been delivered and will be used for preliminary studies.

The European Transonic Windtunnel (ETW) project continues and the status has been reviewed in two recent presentations, at the AGARD FDP Symposium[10] in 1983 and to the Royal Aeronautical Society[6] in 1984. The general features of the tunnel (Figure 9) were given in the AGARD Lecture series "Cryogenic Wind Tunnels"[46] in 1980. Since then the design has been revised in several respects as mentioned in presentations to AAAF[23] in Poitiers and to DGLR[24] in Aachen in 1981 and in the Conveners' report[1] on Cryogenic Test Technology in 1982. Some details of the specification remain to be fixed and discussion will no doubt continue until the last possible moment.

The preliminary design phase (the present phase) has been extended until 1 July 1985. The next phase of the project which will last about two years will be concerned with the preparation of specifications and requests for proposals together with some preparatory studies in particular areas intended to reduce the overall procurement time. Discussions on site selection and other necessary preparations are being pursued actively. The final phase will follow which will include construction, commissioning, calibration and initial operation.

The pilot tunnel (PETW) (Figure 10) for the ETW project has been installed at NLR Amsterdam and commissioning began in March 1984. It will be used to check the aerodynamic performance of the ETW circuit (losses, diffuser performance, flow quality, second throat concept), to perform control studies to validate mathematical models to be used for ETW, and to gain operational experience with a transonic cryogenic tunnel.

Detailed measurements have been made on an aerodynamic test-rig[6] at DFVLR Cologne (Figures 11,12) constructed and operated under contract to ETW. These measurements have largely confirmed the basic circuit design but have also suggested some areas in which some improvements might be obtained.

MODEL DESIGN AND CONSTRUCTION

The recent activity on wind tunnel models in USA has been described at some length in the proceedings of a conference[7] (1979) and a workshop[8] (1982) held at NASA Langley. The papers in these proceedings provide much more detailed information than the Conveners' report, of course. They are essential reading for those concerned with cryogenic test technology, particularly the design and construction of models. Prospective users of the new pressurized cryogenic tunnels will also find them of interest. Since the subjects addressed in these documents are basically the same as those covered in the Conveners' report[1] it is difficult to summarise them without extensive repetitions. Therefore attention will be given to extension of what has been covered in the Conveners' report and to any new material much of which is well-summarized in reference 25. Mandatory criteria for the design, analysis, quality assurance and documentation of wind-tunnel model systems to be tested in specified closed-circuit wind tunnels at NASA Langley are given in reference 26, which supercedes earlier versions. Additional criteria for cryogenic model systems are included covering material selection, specialized analyses, allowable working stress, material properties verification, fasteners and nondestructive examination. Although this document applies only to NASA Langley facilities it will no doubt influence the authors of corresponding documents for other cryogenic facilities.

The combination of high loads and strength limitations on cryogenically acceptable materials will require that model/balance/sting systems (Figure 13) be designed to lower safety factors than for conventional wind tunnels. In turn this will necessitate more rigorous and sophisticated analysis than formerly, together with experimental verification of mathematical models and proof testing in critical cases. All this is now generally agreed and reference 8(6) gives an account of the analytical methods applied to the Pathfinder I model. It is remarked that a goal is to develop an integrated computer program for analysing wind tunnel models.

A recent paper[27] summarizes and gives some examples of the thermal analysis activity performed in support of the design of models for NTF. The experience gained indicates that thermal considerations do not influence the design to the extent originally envisaged. The predicted temperature gradients in the models do not produce stresses large enough to cause problems unless the area sustaining the gradients connects two separate components through pins and fasteners: the loads may then be concentrated at the fasteners instead of being distributed through the material. Similar problems may occur when pins and fasteners connect components of different materials or of different thicknesses. A test programme is recommended to assess load relief by deformation or movement of screws.

The model preparation and test-section access arrangements for NTF are outlined in another paper[8(3)] which will be of interest to prospective users and for comparison with the proposed arrangements elsewhere (eg KKK, ETW). More information on the subject is to be found in reference 28.

Another paper[8(7)] gives a list of a number of research models planned for testing in NTF and later papers[12,13] discuss how these models and some others will be used in the initial research programme. The basic Pathfinder I configuration with an "instrumented" (pressure orifices, thermocouples, buffet gauges) wing (Figures 14,15) is made from Nitronic 40. Alternative wings are available, a solid wing made from PH 13-8 Mo in the 1150 M condition and a wing with flaps and ailerons made from Vascomax 200. There is also a half-size Pathfinder I made from PH 13-8 Mo for tunnel wall interference measurements. Other models are a generalized combat aircraft configuration Pathfinder II (Figure 16) made of Vascomax 200, a set of six bodies of revolution (Figure 17) made from 6061 aluminium alloy, a Shuttle Orbiter (Figure 18) made of A286 stainless steel and fitted with remotely-controlled elevons and rudder/speed brake driven by a dc motor, a supersonic cruise research model (Figure 19) made from Vascomax 200, a flat-plate delta wing model (Figure 20) made from Vascomax 200 with pressure-plotted wing and leading edges, and finally, the existing LANN semi-span wing made of Nitronic 40 which will have to be refurbished for cryogenic testing.

In addition to the NASA activities on models for NTF aircraft constructors in USA have made design studies as follows:

General Dynamics[8(8)]	: manoeuvrable fighter designs F-16XL and F-111/TACT
Lockheed-Georgia[8(9)]	: LANN wing (for oscillating unsteady pressure measurements)
Boeing[8(10)]	: 767 (a model is ready for testing)
Grumman[8(11)]	: X-29A

The design studies at General Dynamics have been subsequently reported[29,30] in more detail. Some of these studies included supporting experimental work and some included cost estimates for design and construction in comparison with those for models for conventional tunnels. A paper[8(13)] from NASA Langley addresses generally the engineering design and fabrication costs of cryogenic wind tunnel models. All these test studies agree that the largest cost increases will potentially occur in the analyses required to establish confidence in the design though these increases should only be significant for low factors of safety. Fabrication cost increases depend on a variety of factors (eg complexity, tolerances and surface finishes, materials, inspection and validation) and any extra costs will depend on the particular example.

The study on the design and manufacture of a combat model (Tornado) for ETW was referred to in the previous report[1]. A summary report[31] of the work so far, prepared jointly by MBB and Dornier, is now available in English. It gives an account of the scope of the study, which was conceived by the authors as the first two phases of a project leading eventually to the construction of a "pilot" model for ETW. Among the subjects addressed are model sizing, accuracy requirements, model deformation, stressing, fatique life, material selection and outline design of a model. Although this study is of wide interest because of its survey of a range of model-design and construction issues it should be noted that there will no doubt be other pilot models for ETW and no firm decisions have yet been taken by the project.

The European experience of actual construction of models for cryogenic tunnels has been limited so far to making two-dimensional models for testing either in the ONERA T2 tunnel or in the 0.3 m TCT at NASA Langley. Accounts have been given of the construction of such models by ONERA on one hand and jointly by DFVLR and NASA on the other. The ONERA paper[9(19)] is a fairly comprehensive account of the construction of a pressure-plotting CAST 7 model of 150 mm (5.9 inch) chord and 390.4 mm (15.37 inch) span for T2. Before particular features of the construction were adopted some test specimens were made and subjected to temperature cycles. The material selected was a maraging steel (Marval 18) used in the annealed state and the various parts of the model were assembled by electron-beam welding. Some doubts about the reliability of tin soldering at low temperature led to the use of a Ciba-Geigy resin (XF 161-162) for fixing the pressure tubes. 71 pressure tappings of 0.3 mm (0.012 inch) diameter and 32 of 0.1 mm (0.004 inch) (Figure 21) were provided using small cylindrical inserts in which the actual pressure holes were drilled. Electron-beam drilling was found to give mis-shapen holes and "laser-beam drilling would have given similar results".

The DFVLR/NASA paper[9(12)] is a similar account of the construction of CAST 10-2/DOA2 and DFVLR R4 models (Figure 22). They were designed and constructed in Germany guided by experience from NASA Langley. The steel was AISI type 304 and the models were made in two halves (top and bottom) brazed (silver-soldered) together.

A total of 90 pressure orifices of 0.3 mm (0.012 inch) were fitted in each airfoil. The pressure tubes were brazed in position in each half of the airfoil and the pressure orifices were drilled into the surface as a final operation after heat-treatment of the halves, brazing together, cyclic cooling to cryogenic temperatures and contouring of the surfaces. After the tests the model geometry was checked and the only permanent change noted was an increase in thickness by 0.03 mm (0.0012 inch) in a maximum thickness of 18.24 mm (0.718 inch) or about 0.16%.

These examples of model design and construction in Europe are interesting because they exhibit different approaches to similar goals, summarized below. Such detailed accounts of model construction are rare but it is to be hoped that these will be followed by others.

	ONERA	DFVLR/NASA
size	span 390.4 mm (15.37 inch) chord 150 mm (5.9 inch) CAST 7	span 202.69 mm (7.97 inch) chord 151.4 mm (5.96 inch) CAST 10-2 and DFVLR R4
pressure orifices	32 x 0.1 mm diameter 71 x 0.3 mm diameter inserts into surface	90 x 0.3 mm diameter drilled in surface
pressure tubes fixing	Ciba Geigy XF 161-162 resin	silver solder Ag 72%, Cu 28%
steel	Marval 18 maraging steel in annealed state	AISI 304 stainless steel
assembly	two halves and a leading edge electron-beam welded together	two halves brazed together

Sting design has been considered in papers[8(8),29,30], from General Dynamics. An attempt was made to design a composite sting but the problems of differential thermal expansion coefficients could not be overcome. The general problem of sting design has been the subject of ONERA papers [9(13),21] which present some results which make it possible to discern the dynamic pressure limitations related to possible sting geometries for particular aircraft (eg Airbus A 300 or Mirage 2000). According to this analysis the main dynamic pressure limitation comes from the risk of static divergence for the civil aircraft. On the other hand, for the combat aircraft the main limitations may be the strain in the sting or possibly the balance capacity and risk of contact at the base, especially if the internal flow has to be simulated.

MATERIALS

Further information[7,8,25] has been published on the work done at NASA Langley on materials for models, balances and stings. Material selection, availability and cost considerations for cryogenic wind tunnel models have been discussed. The comment is made that material selection for cryogenic models is a similar problem to that for conventional models with the added requirements of fracture toughness and alloy phase stability. To ensure the required properties materials should be ordered to tight specifications with guaranteed properties if possible. Since the material cost, while high compared to common alloys, is a small fraction of the total model cost it should not be a major factor in material selection.

At NASA Langley all basic alloy groups have been considered but only the iron and aluminium alloys appear to be viable candidates. As loads increase the number of available alloys is severely constrained by toughness requirements. The material selection for the Pathfinder I was further restricted by long delivery times before Nitronic 40 was chosen. The alloys under study at NASA Langley are shown in Figure 23 with emphasis on A 286, Vascomax 200 and PH 13-8 Mo. The Fe-12Ni alloys[8(18)] developed at NASA Lewis appear promising for the future. NASA Langley experience has shown long delivery times for all candidate materials, 26 to 52 weeks not being unusual for high quality material to tight specifications. Further, experience with the Pathfinder I model is said to have demonstrated the need for such material even at premium prices. According to references 25 and 26 it is imperative that all metallic alloys used for cryogenic models be given a 100 percent volumetric nondestructive examination because the presence of flaws could severely jeopardise the model system structural integrity.

A multi-step heat treatment[25,32] to refine grain size appears to be a promising technique to improve the toughness of many high strength materials. Significant improvement in the cryogenic toughness of commercial high-strength martensitic and maraging steels has been demonstrated through the use of grain-refining heat treatment. Charpy impact strength at 77 K was increased from 50 to 180 percent for the various alloys without significant loss in tensile strength. The grain sizes of the 9-percent Ni-Co alloys and 200-grade maraging steels were reduced to 1/10 of the original size or smaller, with the added benefit of improved machinability. The grain refinement process (Figure 24) consists of multiple heating and cooling cycles alternating between the austenitic region and the dual-phase ferrite-plus-austenite region to reduce the grain size. The grain refinement cycles are followed by annealing and age hardening or tempering as required to restore strength. This technique should permit alloys with ultimate strengths of 1500N/mm^2 to 1800 N/mm^2 (220 to 270 ksi) to receive consideration for cryogenic service.

One of the problems uncovered in the course of building and testing models for the 0.3 m TCT at NASA Langley is that of dimensional instability[8(14),25,33,34,35]. Small dimensional changes are important in wind tunnel models being tested at high Reynolds number because of the stringent requirements on shape and surface smoothness. Initial problems were encountered with two-dimensional models made of 15-5PH stainless steel which warped significantly after testing in the 0.3 m TCT. The two basic mechanisms that can lead to warpage are:

1. metallurgical structural instability in which one phase transforms partially or completely into a second phase which has a different crystal structure and volume and
2. deformation due to the generation or relief of unbalanced stresses.

In the case of the 15-5PH airfoils it is highly probable that metallurgical instability was responsible for most of the warpage. But, even in metallurgically stable materials, temperature cycling can alter the residual stresses and lead to dimensional changes. A configuration for a standard specimen for dimensional stability tests has been proposed[8(14),25,34] (Figure 25). Other investigations, at Lockheed-Georgia, into the stability of existing two-dimensional airfoils, of models in various stages of manufacture, and of flat specimens of candidate materials are reported briefly in reference 8(15).

A paper[9(4)] from MBB has considered the selection of austenitic stainless steels for model construction for cryogenic wind tunnels. It mainly reviews and comments on the literature on the dimensional stability as affected by the austenitic-martensitic phase transformation and suggests which types might be expected to meet the severe requirements of cryogenic model building.

A detailed study of the characteristics of Nitronic 40 is reported in reference 36. This paper, and remarks elsewhere about experience with Pathfinder I (made from Nitronic 40), suggest that quality control problems were encountered with at least one batch of the material. A further paper[25] on the fracture toughness and flaw growth in Nitronic 40 at cryogenic temperatures is related particularly to Pathfinder I wing construction.

Various solder alloys are being examined at NASA Langley to determine their suitability for use at low temperatures. Solders which are high in tin content can fail at low tempratures due to allotropic transformation of the familiar "white" tin into a "grey" tin powder; also tin alloys suffer low temperature embrittlement. A possible replacement for a previously-recommended alloy (95% tin - 5% silver) is 95% tin - 5% antimony. Antimony retards the formation of "grey" tin. Other alloys being considered are 50% tin - 49.5% lead - 0.5% antimony; 37.5% tin - 37.5% lead - 25% indium; and 50% lead - 50% indium. Lead and indium remain ductile to low temperatures.

The matter of suitable adhesives and filler materials continues to receive attention but, as pointed out in reference 8(17), the requirement for a short setting time on cold model surfaces presents a difficult problem. The commercially-available products in current use at NASA on the 0.3 m TCT are listed. More recent work on epoxy resins incorporating carbon powders is reported in reference 25.

In addition to this work NASA Langley have conducted a test programme[25,37] on the tensile load capability and failure modes of different sizes and lead types of A-286 stainless steel screws at room temperature and at 135 K (- 275°F). The results are being used in the design of NTF models. Tests have also been made of five locking systems (Heli-coil, Spiralock thread form, Loctite, Crest, Al-filled epoxy) using A-286 screws in four steels and one aluminium alloy. In the absence of loads cryogenic cycling generally produced decreases in breakaway torque. Again in general, most systems were found to be effective retention devices but there are differences between them with respect to ease of application, clean-up, and re-use.

A paper[9(20)] from IMFL, now part of ONERA, reviews the low temperature behaviour of a wide range potentially usable materials for cryogenic wind tunnel models including metallic alloys, composites and plastics. In addition the cryogenic behaviour of bonded (glued), screwed and welded joints is discussed and some experimental results shown. This paper is welcome in that it makes the work which IMFL has done in this subject accessible to a wider audience.

There has been some exploration of possibilities concerning aero-elastic models for ETW. A paper[9(8)] from MBB includes brief results of some fatique tests on sandwich specimens consisting of carbon-fibre skins with internal structures of Conticell C 60 foam, Rohacell 51 foam and Nomex honeycomb. The specimens were tested up to a million cycles at temperatures down to about 150 K. It was concluded that the foams could be used for flutter model construction but that the honey-comb was unsuitable. The paper goes on to make preliminary proposals for the design of wings for flutter models of a transport aircraft (A 310) and a delta-wing combat aircraft. Finally, some tests on hydraulic rudder actuators at temperatures down to 140 K are briefly described: it is shown that, if suitable insulation and heating measures are taken, such actuators can be used with no particular difficulties.

Some work at IMFL on the construction of a cryogenic flutter model fin for a Mirage 2000 has been described[9(20)]. ALthough the real aircraft has a composite material fin the model fin has been made with 0.25 to 0.35 mm aluminium alloy AU2GN skins and a honeycomb filling (AEROWEB 5052 with 3 mm cell size). The bonded joints were made with epoxy film Redux BSL-312/4 of 0.11 mm thickness. The leading edge and the fin tip were made of the glass-fibre composite Fibredux 920. The vertical rudder was filled with Ciba FW 650 epoxy foam: the 0.2 mm AU4G skin was chemically shaped. Vibrational and fatigue tests on the model fin have been made at steady temperatures down to 120 K which are said to prove the concept.

Though not concerned directly with flutter and buffet model construction an interesting paper[38] assesses the future roles of the NTF and the TDT (Transonic Dynamics Tunnel) at NASA Langley. This will be of main interest to prospective users of Langley wind tunnels but the points raised may interest users of European tunnels concerned with flutter and buffet investigations.

SURFACE FINISH

There have been no further published papers on the matter of surface finish requirements. Some preliminary results have been presented[8(20)] from the joint NASA/NBS project on surface finish measurement studies of which the objectives were (1) to evaluate the performance of stylus instruments for measuring the topography of NTF model surfaces both for monitoring during fabrication and for absolute measurements (2) to measure and characterize the true three-dimensional topography of NTF model surfaces so that their characteristics could be related back to distributed particle surfaces and (3) to develop a light-scattering instrument for rapid assessment of the surface finish of a model.

It has been shown that workshop-grade stylus instruments can damage the surface of models and that their use for monitoring fabrication can lead to surface finishes that are substantially out of range in critical areas of the leading edges. In connection with the third objective the capabilities of major surface topography instruments were compared in terms of a wavelength/slope space. This illustrated the limited spatial wavelength bandwidth of light-scattering instruments. The point is made that in selecting a measurement instrument it is important to know what range of irregularity spacings is of significance for aerodynamic effects.

FORCE BALANCES

The development of strain gauge balances for NTF (Figure 26) has continued[8(21)] and the details of nine balances have been mentioned in various diameters from 19 to 60 mm (0.75 to 2.375 inch) with normal force ranges from 710 to 28910 N (160 to 6500 lbf). Improved strain gauging techniques have lead to large reductions in the variation of zero off-set with temperature.

A recent paper[39] describes aerodynamic force component measurements on a 75° delta-wing model with sharp leading edges made with a three component internal strain gauge balance in the 0.3 m TCT at stagnation temperatures of 300 K, 200 K and 110 K at Mach numbers of 0.3 and 0.5 and angles of attack up to 29°. The results indicate that it is feasible to acquire accurate force and moment data while operating at steady-state conditions in a cryogenic wind tunnel. Tests with the same model over approximately the same range of conditions have recently been conducted using a balance designed and built at NLR Amsterdam and partially funded by the ETW project. The comprehensive set of data from this experiment is still being analysed: it includes measurements of model and balance temperatures during changes in tunnel conditions.

In Europe work on strain gauge balances is proceeding in several places with the objectives of understanding the problems and developing techniques without the immediate necessity of measuring forces in cryogenic wind tunnels although that will soon be required. The balances under way are those mentioned previously and they have all been tested in cryogenic chambers at uniform temperatures. It has been realised that, in ETW at least, balances will have to operate at least part of the time with temperature gradients and the testing has now extended to exploration of the effects of steady and transient gradients. Some computer studies[9(21)] have been made in order to understand the possible magnitude and development with time of the temperature field in and around a model/balance/sting arrangement under various circumstances (tunnel cooldown-or-warm up, model temperature conditioning before or during a run, set-point changes during runs). Further studies will be undertaken to take into account more realistic configurations and the effects of convection and conduction in the space inside the model around the balance.

A cryogenic chamber with low-speed flow has been constructed at RAE Bedford (Figure 27) with the objective of providing a facility to test model/balance/sting configurations. Some preliminary tests have shown the strong effects on axial force output of a convection shield around the balance. In the future it can be employed to provide experimental checks on the computer models.

One of the recent events of significance has been a meeting of strain gauge balance specialists at ONERA Modane on the occasion of the retirement of M. Dubois. It was an attempt to provide a rare opportunity for the workers in this field to meet and discuss the technical issues. The principal subject of interest was the behaviour of balances at various steady state temperatures down to about 100 K and the effects of temperature gradients both steady-state and transient. It is of course much more difficult to study such cases than overall steady-state conditions with no gradient.

INSTRUMENTATION

Model deformation measurements. The high model loads to be encountered in NTF will cause large model deflections leading to the requirement to measure model deformation. The goal set is to be able to measure peak deflections of up to 75 mm (3 inch) with accuracies to within $\pm$ 0.06 mm (0.0025 inch) over an area 1 m (39 inch) square as the model pitches through an angle of 30°.
Two separate systems will be available to determine model deformation during testing. The first, a video based system described in reference 40, utilizes passive targets on the models (painted on, for example), two standard television cameras, two monitors, and conventional film reader to quantify the information contained in photographic pictures of the images shown on the monitors. The second, an image dissector camera based system described in references 8(22),41,42, utilizes active targets (light emitting diodes) and near real-time computerized data reduction system. The video based model deformation system will be utilized for all the initial models with the more complex image dissector based system becoming available a little later.

Model pressure measurements. As previously reported, pressure measurements[8(23)] on NTF models will be made using electronically-scanned pressure transducers. The system compromises multichannel pressure modules, a pressure calibration standard and a system controller. The pressure modules will be mounted in temperature-controlled insulated enclosures. Some illustrations are given in reference 8(23) of the 192 channel package for Pathfinder I. The module volume/channel ratio has been improved to 1.64 cm^3/channel for 32 channel modules and 1.48 for 48 channels.

The inertial angle of attack measuring instrumentation which is also shown in the Pathfinder I illustration (Figure 28) also requires temperature control and occupies a substantial volume inside the relatively large fuselage of the transport model. Tne limitations of such accelerometers are that they have a slow response, they are fragile and labour-intensive, multiple instruments are required for 2 axes and a large package (with many wires) results. Therefore there is an interest in an externally-mounted optical system such as that developed by Boeing which has been previously described and further details of which are given in reference 8(24). Both inertial and optical system will be available for NTF.

FLOW VISUALIZATION AND LASER VELOCIMETRY

The main source of new information on these subjects is the proceedings[16] of a workshop held at NASA Langley in March 1982. According to the preface of this volume the motivation for the workshop was the construction and approaching commissioning of the National Transonic Facility (NTF) at Langley Research Center (LaRC). Because the NTF will achieve significantly higher simulated Reynolds number flight conditions than any other wind tunnel in the world and therefore will occupy a unique position among ground test facilities, every effort is being made to ensure that it is equipped or provisions are made for those flow field diagnostic techniques that potential users from industry, universities, and government feel are necessary. The need for flow visualization and laser velocimetry were highlighted in a meeting held at LaRC and reported in NASA Conference Publication 2183 entitled "High Reynolds Number Research - 1980"[47]. As a result this workshop was organized, and its purpose was threefold:
1) provide a state-of-the-art overview;
2) provide a forum for industry, universities, and government agencies to address problems in developing useful and productive flow visualization and laser velocimetry measurement techniques and
3) provide discussion of recent developments and applications of flow visualization and laser velocimetry measurement techniques and instrumentation systems for LaRC wind tunnels including the 0.3 m TCT and plans for the NTF.

Concerning NTF the provisions for optical access[16(1)] to the test section have been described and the constraints of space and environment imposed by the plenum and the model acces arrangements outlined. A total of 56 windows to be used for viewing or lighting were planned (Figure 29). This dramatically illustrates the problems which arise in trying to meet all the users' requirements and how more complex test-section configurations than NTF would require some compromise.

The rest of the presentations at the workshop can be divided into two sections, flow visualization and laser velocimetry.

Flow visualization. The need for an optical method of transition detection[16(2)] in NTF, particularly for tests by transport aircraft constructors, was argued. It was accepted that infrared thermography was not a promising method at low temperatures. Another manufacturer proposed that high priority should be given to development of a surface flow visualization technique [16(3)]. The reasons for doing so were explained and the charasteristics of an ideal system were specified. Another paper[16(4)] from the same company described the present state-of-the-art and some of the practical difficulties. The necessity for a wind-on system for dispensing the indicator to the model surface was suggested because of the expense of using a one-shot pre-run application for routine use. The advantages of a delivery system consisting of a sintered porous metal strip inset into the model surface were discussed. A flame-spray process which involves blowing semi-molten powdered metal into a slot machined in the model surface has been tried on small specimens. The surface contour is machined to shape afterwards.

The feasibility of optical methods of flow visualization in cryogenic facilities has been examined at NASA Langley in various experiments in the 0.3 m TCT and in a cryogenic chamber with windows: this work has explored such subjects as image degradation[16(6),43] in observation of optical targets on a model, comparisons[16(5)] of schlieren, shadowgraph, and moiré systems and comparisons[16(7),44] of schlieren, shadowgraph and interferometer reconstructions obtained from holographic recordings. These tests indicate a general trend towards worsening image quality with increased pressure and decreased temperature though the relative contributions of the various factors has not been precisely determined.

Laser velocimetry. Trials[16(8)] have also been made in the 0.3 m TCT with both a laser Doppler velocimeter and a laser transit anemometer. In the first case a 15mW helium-neon laser was used in a forward-scatter system with a high-speed burst counter and an online digital computer. No seeding was introduced, reliance being placed on the already-present liquid nitrogen droplets in the flow, which appeared to be sufficient. Velocity measurements were made in the free stream and at a point above an NACA 0012 aerofoil at zero incidence. The results were sufficiently encouraging for the further work to be recommended: vibration was not a problem.

In the case of the laser transit anemometer[16(9)] it was confirmed that the particle concentration was sufficient to make velocity and flow angle measurements under all tunnel conditions. A horizontal traverse was made across a shock on a NACA 0012 aerofoil at zero incidence and $M = 0.85$ to compare measured and calculated velocities.

The installation and operation of a laser velocimeter in NTF has been discussed[16(10)] The operational requirement is to measure flow field angularity with an accuracy of 0.01 degree at velocities up to 250 m/s. The device chosen for initial use is a laser transit anomemeter on grounds of compactness and simplicity of installation, since it has to fit in the plenum, and has performance comparable to a laser Doppler velocimeter.

There are several engineering problems that remain to be solved, according to the authors of this study, which include compatibility with tunnel operating procedures, simplifying the installation, efficient seeding techniques to achieve measurement times of the order of a second, and improved accuracy in angular measurement.

It is clear from the work described so far in the whole field of optical methods of flow visualization and measurement that a substantial and serious development effort is going to be necessary if these methods are to be available for routine use in cryogenic tunnels.

FLOW PHENOMENA

Non-adiabatic wall effects. The need to match the in-flight aircraft surface thermal conditions when testing in a wind tunnel has been studied in a complementary experimental and computational investigation[20]. The experimental programme took place in the McDonnell Douglas 1-CWT using a two-dimensional aerofoil. The results were compared with computations using a theory by Inger. Based on the experimental results, confirmed in part by the computations, it was concluded that the temperature of the model should be within 1% of the adiabatic wall value as a maximum, and even closer when separation effects are important.

A preliminary study[9(18)] on this question has been made in the ONERA/CERT T2 wind tunnel with adaptive walls using a two-dimensional CAST aerofoil at $M = 0.76$ and zero incidence. The aerofoil was heated to 320 K before runs in which the flow temperature slowly varied from 290 K to 280 K. Transition was fixed by 0.03 mm (0.001 inch) high carborundum bands at $x/c = 7\%$ on both surfaces. The wall temperature ratio varied across the aerofoil, of course: the value at $x/c = 30\%$ was taken as the reference condition. The influence of changing the Reynolds number from 6.7×10^6 (based on 0.2 m chord) was examined by testing at two stagnation pressures (2.34 and 3.70 bar).

To complement the experimental results computations were also performed for the same conditions. The overall conclusions were that this preliminary study did not show fundamental deviations due to the effect of wall temperature except in shock-wave posi-

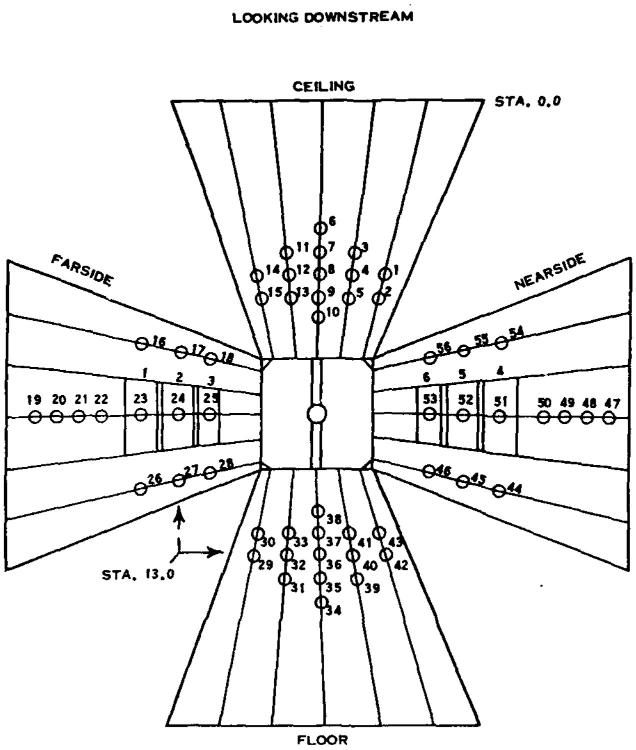

FIGURE 29
NTF TEST SECTION
OPTICAL ACCESS

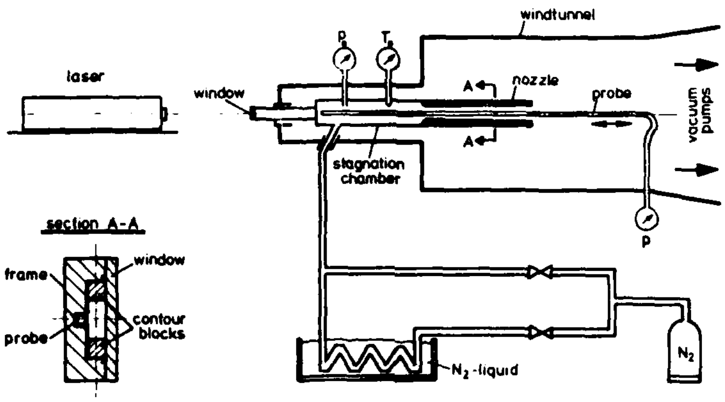

FIGURE 30 DFVLR STREAM TUBE DUPLICATION APPARATUS

FIGURE 26 NTF FORCE BALANCES

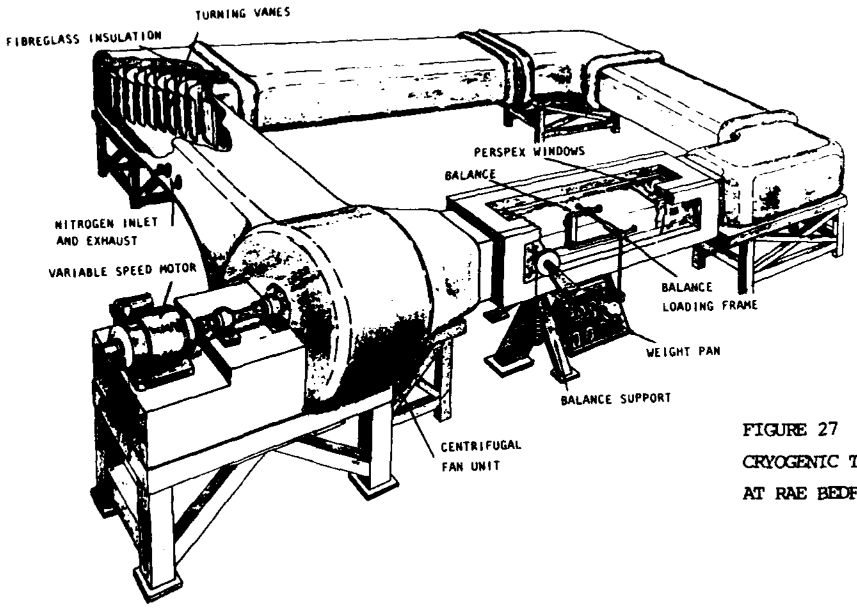

FIGURE 27
CRYOGENIC TEST CHAMBER
AT RAE BEDFORD

FIGURE 28
ELECTRONICALLY
SCANNED PRESSURE
MODULES FOR
PATHFINDER 1

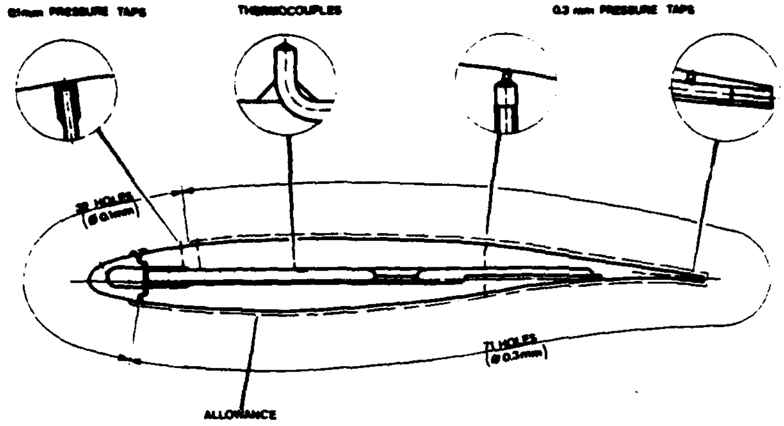

FIGURE 21 CAST - 7 AIRFOIL MODEL (ONERA)

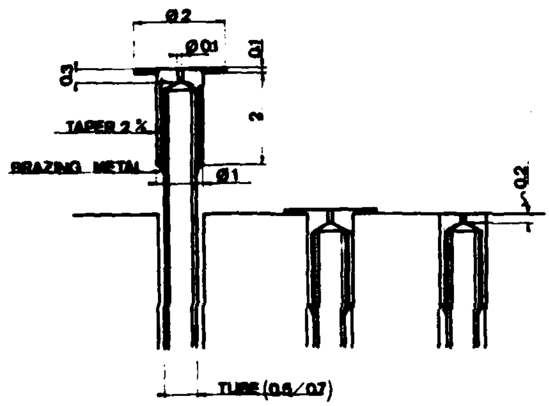

FIGURE 22 PRESSURE HOLES OF AIRFOIL MODEL

I AUSTENITIC
1. 300 SERIES STAINLESS STEELS
2. NITRONIC STAINLESS STEELS
3. A-286

II MARTENSITIC
1. VASCOMAX 200
2. PH 13-8 Mo STAINLESS STEEL
3. HP 9-4-20

III FERRITIC
1. 9 Ni (ASTM A353)
2. Fe-12 Ni (LEWIS RESEARCH CENTER)

FIGURE 23 ALLOYS STUDIED AT NASA LANGLEY

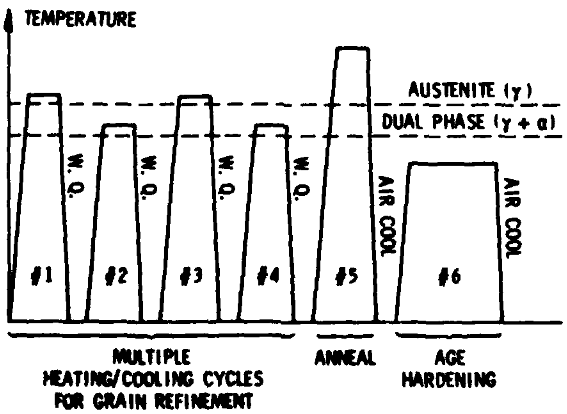

FIGURE 24 TYPICAL GRAIN-REFINING HEAT TREATMENT

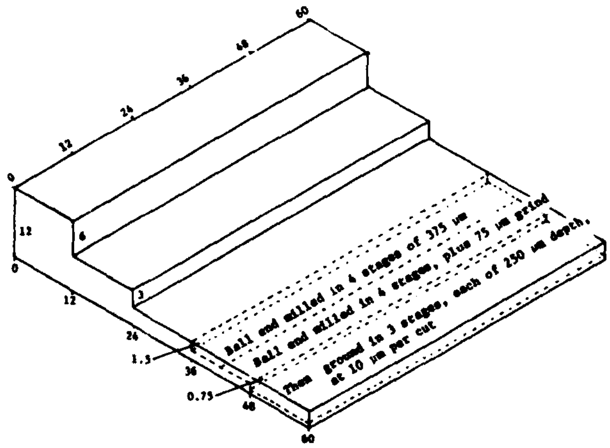

FIGURE 25 SPECIMEN FOR WARPAGE EVALUATION

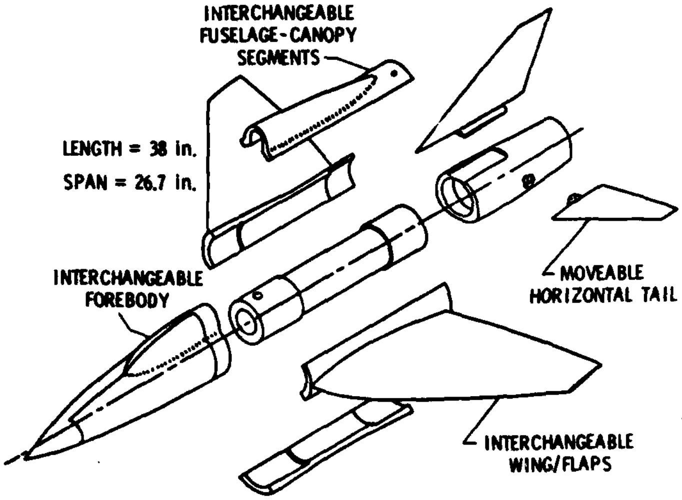

FIGURE 16 PATHFINDER II MODEL

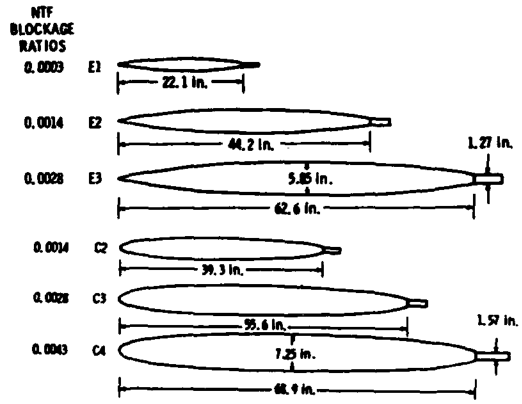

FIGURE 17 BODIES OF REVOLUTION FOR BLOCKAGE ASSESSMENT IN NTF

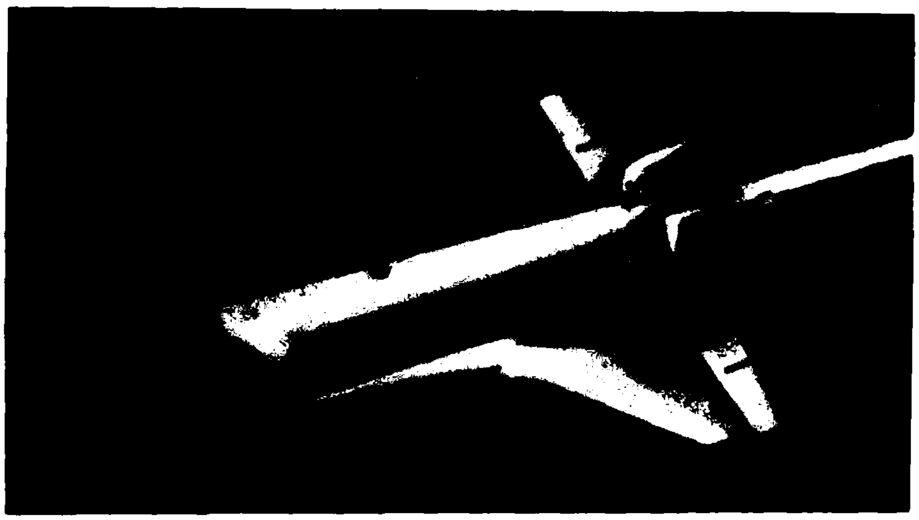

FIGURE 18 SHUTTLE ORBITER MODEL

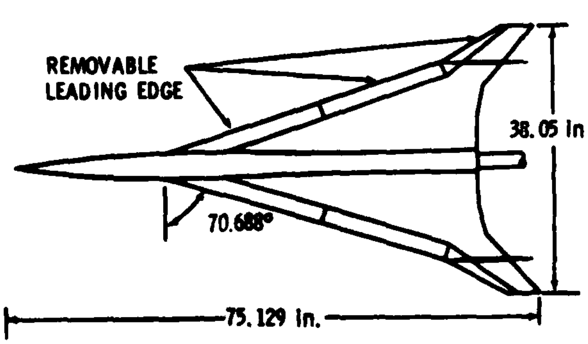

FIGURE 19 SUPERSONIC CRUISE RESEARCH MODEL

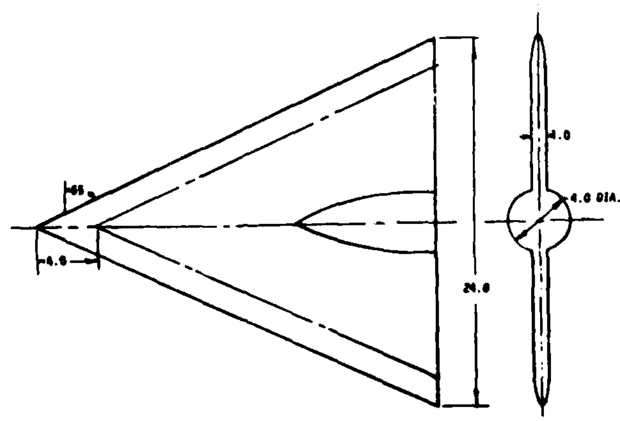

FIGURE 20 FLAT-PLATE DELTA WING MODEL

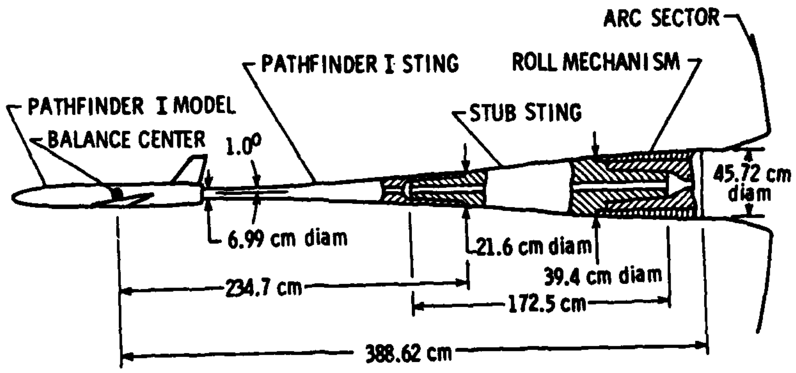

FIGURE 13 PATHFINDER 1 STING CONFIGURATION

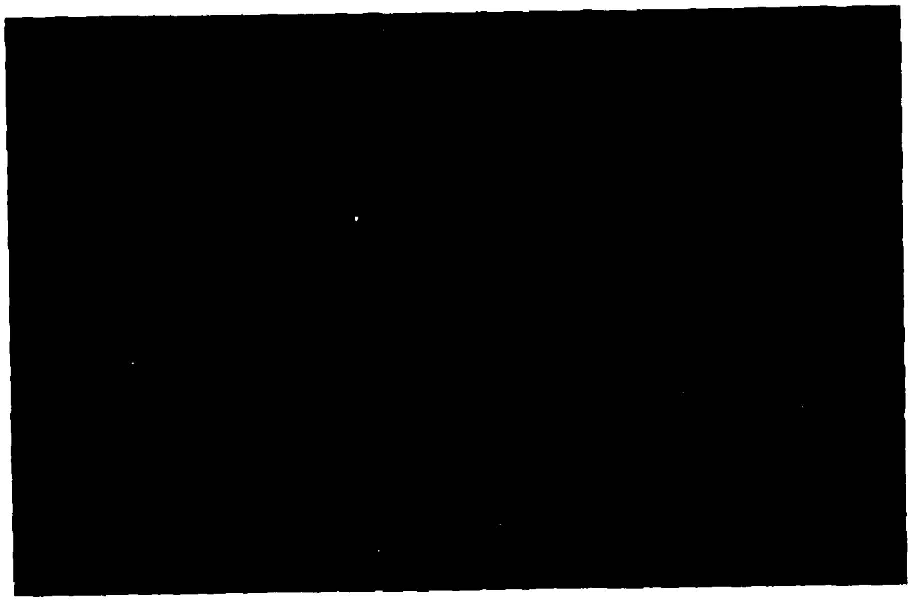

FIGURE 14 PATHFINDER 1 MODEL

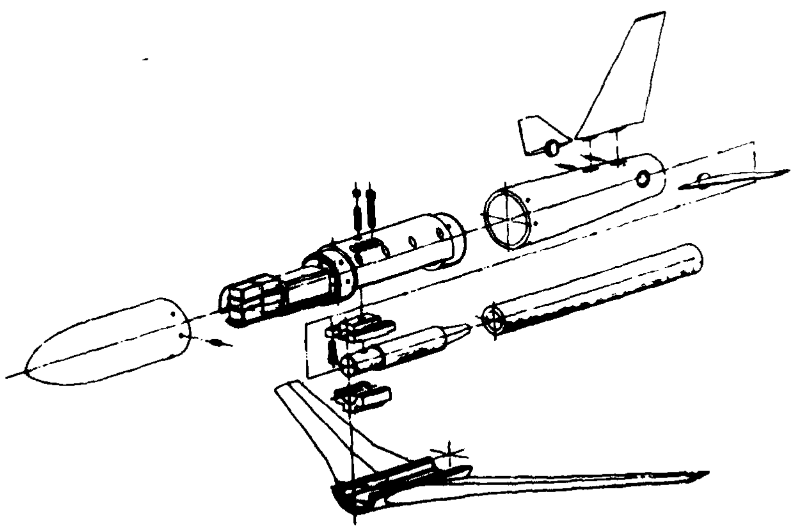

FIGURE 15 PATHFINDER 1 MODEL

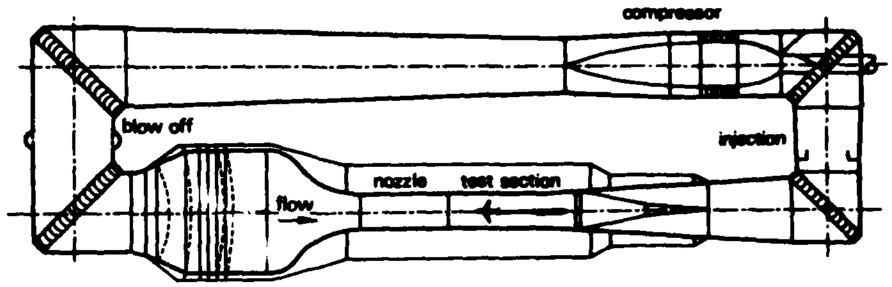

FIGURE 9 AERODYNAMIC CIRCUIT OF ETW

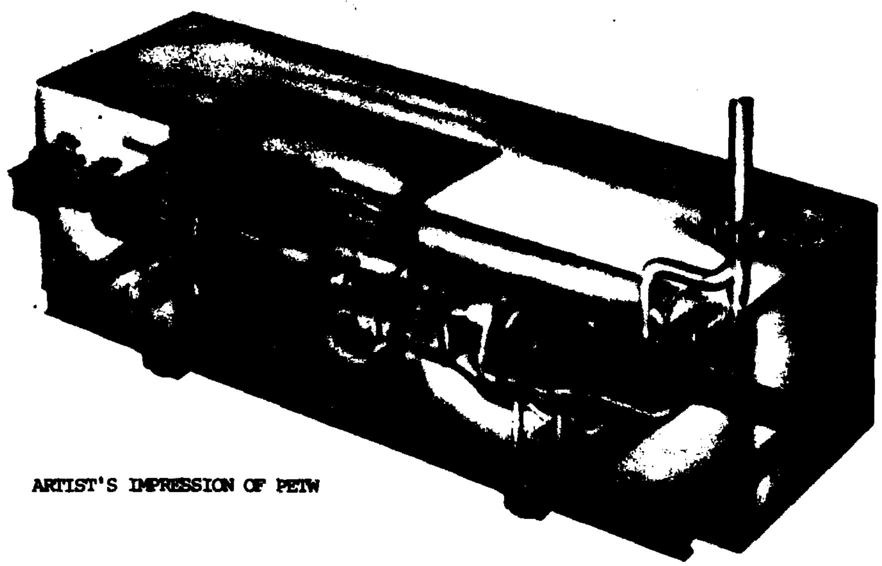

FIGURE 10 ARTIST'S IMPRESSION OF PETW

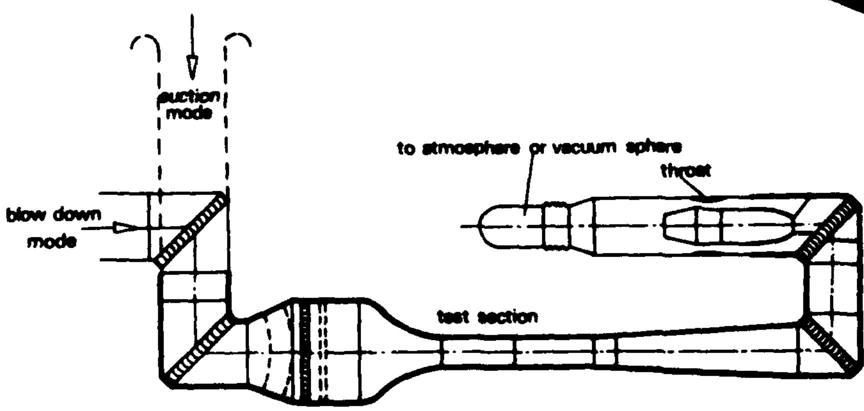

FIGURE 11
PLAN VIEW OF TEST RIG
AT DFVLR-COLOGNE

FIGURE 12
TEST RIG AT DFVLR-COLOGNE

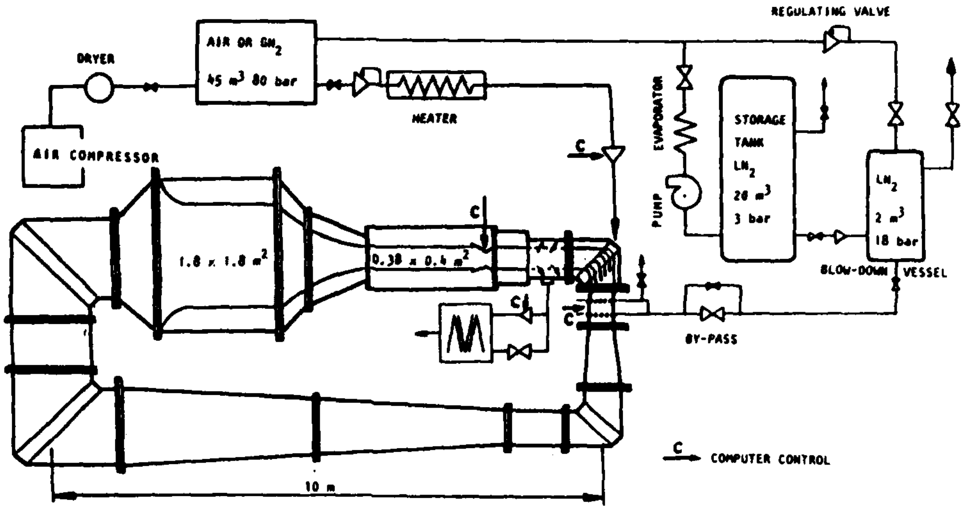

FIGURE 5 TUNNEL CHARACTERISTICS OF T2

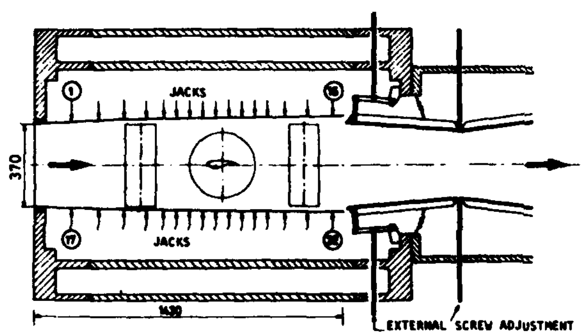

FIGURE 6 T2 ADAPTIVE WALL TEST SECTION

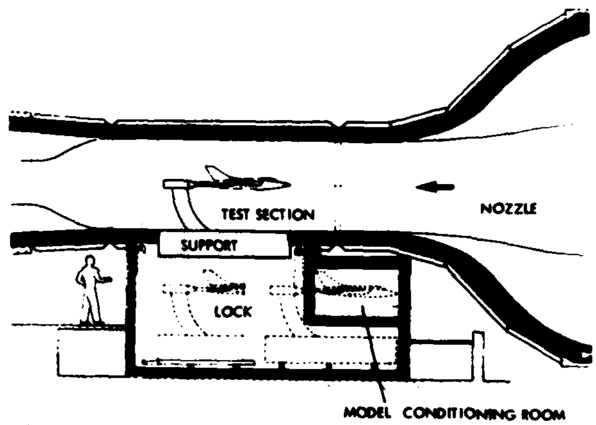

FIGURE 7 KKK TEST SECTION INCLUDING ACCES LOCK AND MODEL CONDITIONING ROOM

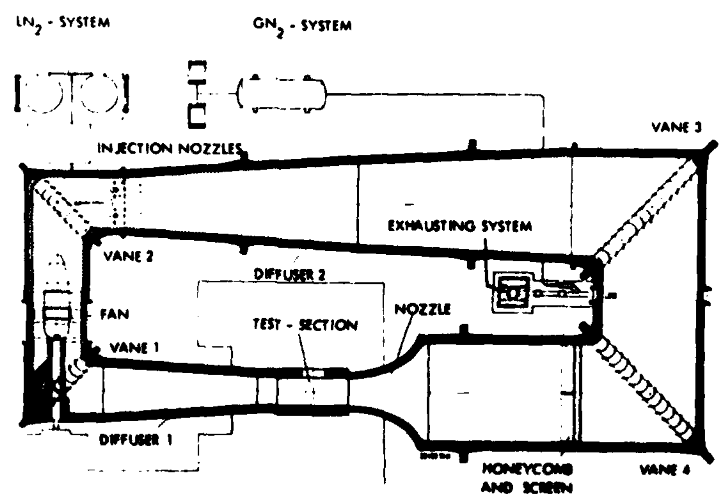

FIGURE 8 KKK TUNNEL CIRCUIT

MEASUREMENTS

- M, P, AND T VARIATIONS
- COMPONENT LOADS
- VARIABLE GEOMETRY SETTINGS
- FAN PERFORMANCE
- CONTROL RESPONSE PARAMETERS
- REPEATABILITY

LOCATION

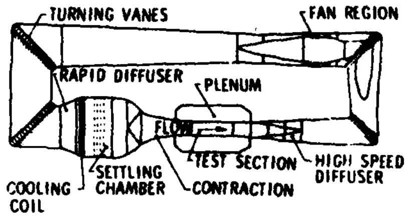

FIGURE 1 NTF CALIBRATION - TUNNEL CHARACTERISTICS

- FLOW DYNAMICS
  - HOT WIRE MEASUREMENTS
  - 10° TRANSITION CONE
- WALL EFFECTS
  - BODIES OF REVOLUTION/3 SIZES
  - PATHFINDER MODELS/2 SIZES
- COMPARISON WITH OTHER TUNNELS
  - PATHFINDER 1 (ARC 11 FOOT)
  - SHUTTLE ORBITER
  - 767 (ARC 11 FOOT AND BOEING W.T.)
- COMPARISONS WITH FLIGHT
  - 767
  - SHUTTLE
  - F-111 TACT
  - X-29

FIGURE 2 NTF CALIBRATION - DATA QUALITY

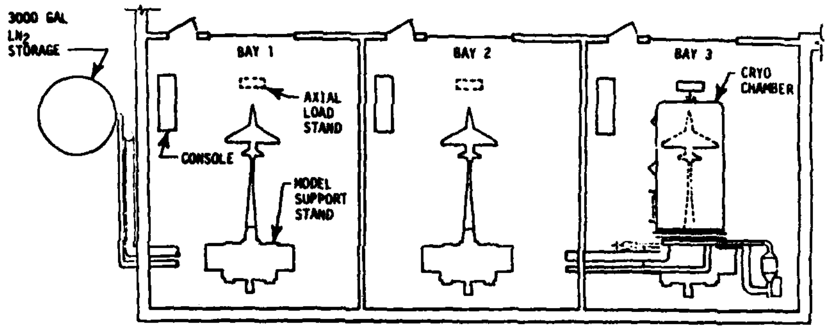

FIGURE 3 NTF MODEL PREPARATION BAYS

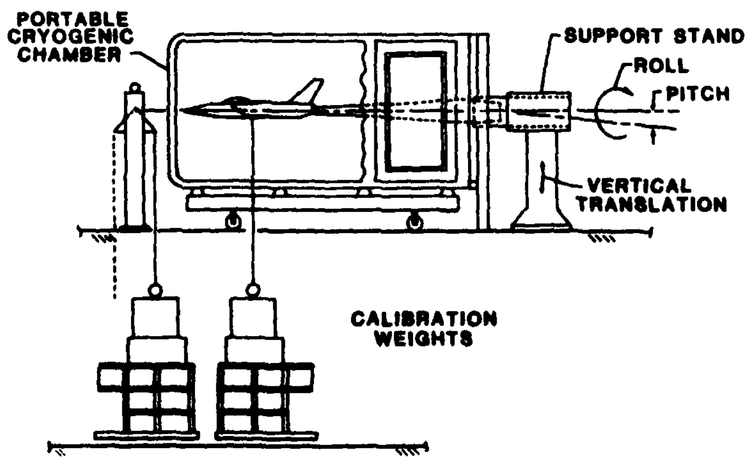

FIGURE 4 NTF MODEL CHECKOUT EQUIPMENT

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43. Snow, W.L.; Burner, A.W.; Goad, W.K.: Image degradation in Langley 0.3-meter Transonic Cryogenic Tunnel, NASA TM 084550 (1982)

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47. High Reynolds Number Research - 1980, NASA Conference Publication 2183 (1980)

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   (1) Fuller, Dennis E.: Provisions for non-intrusive flow-evaluation tools in the National Transonic Facility
   (2) Fancher, M.F.: The need for an optical transition detection system in the NTF
   (3) Bengelink, Ronald L.: Surface flow visualization requirements for testing in NTF
   (4) Crowder, James P.: Surface flow visualization using indicators
   (5) Rhodes, D.B. and Jones, S.B.: Flow visualization in the Langley 0.3- meter Transonic Cryogenic Tunnel and preliminary plans for the National Transonic Facility
   (6) Snow, W.L.; Burner, A.W. and Goad, W.K.: "Seeing" through flows in Langley's 0.3-meter Transonic Cryogenic Tunnel
   (7) Burner, A.W.; Snow. W.L.; Goad, W.K.; Helms, V.T. and Gooderum, P.B.: Flow field studies using holographic interferometry at Langley
   (8) Gartrell, Luther R.: Laser Doppler velocimetry application in the Langley 0.3-meter Transonic Cryogenic Tunnel
   (9) Honaker, W.C.: Velocity and flow angle measurements in the Langley 0.3-meter Transonic Cryogenic Tunnel using a laser transit anemometer
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(7) Bradshaw, James F.: Status of NTF models
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(9) Firth, George C.: LANN wing design
(10) Whisler, William C.: NTF model: A new breed
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(12) Whisler, William C.: Cost factors for NTF models
(13) Boykin, Jr., Richard M. and Davenport, Jr., Joseph B.: Engineering and fabrication cost considerations for cryogenic wind tunnel models
(14) Wigley, David: Dimensional stability considerations for cryogenic metals
(15) Firth, Geroge C.: Metallic alloy stability studies
(16) Wigley, David: Metallurgical studies of Nitronic 40 with reference to its use for cryogenic wind tunnel models
(17) Rush, Homer F.: Cryogenic materials selection, availability, and cost considerations
(18) Stephens, Joseph R.: Development of tough, strong, iron-base alloy for cryogenic applications
(19) Morgan, William H.: Wire electric-discharge machining and other fabrication techniques
(20) Teague, E. Clayton: Surface finish measurement studies
(21) Ferris, Alice T.: Strain gauge balances and buffet gauges
(22) Holmes, Harlan K.: Model deformation system
(23) Kern, Frederick A.: NTF model pressure measurements
(24) Finley, Tom D.: Angle of attack system

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(2) Schoenmakers, T.J.: The development of a strain-gauge balance for cryogenic wind tunnels
(3) Fuijkschot, P.H.: Peanuts - the PETW data system
(4) Luck, S.: The austenitic-martensitic phase transformation and its influence on the design of models for cryogenic wind tunnels
(5) Luck, S.: Experimental tests on accelerometers and pressure transducers for cryogenic wind tunnel models
(6) Zacharias, A.: Parameter and design studies for the use of wind tunnel models in the ETW
(7) Schimanski, D.: Investigations and tests of mechanisms for wind tunnel models under cryogenic conditions
(8) Hönlinger, H. and Mussmann, D.: Some aspects of aero-elastic models for cryogenic wind tunnels
(9) Lorenz-Meyer, W. and Greawe, E.: Development of a cryogenic wind tunnel balance
(10) Wagner, B.: Estimation of simulation errors in the European Transonic Wind Tunnel
(11) Düker, M.: Condensation studies in cryogenic nitrogen expansions
(12) Schächterle, G., Ludewig, K.H., Stanewsky, E., Ray, E.J.: Design and construction of two transonic airfoil models for tests in the NASA Langley 0.3 m TCT
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material properties. The necessary resources are already more or less available at NASA Langley Research Center but it will take some time for them to be developed and applied in Europe. If the time to design and build models is to be reduced in future a serious effort must be made to develop the methods.

The real problems of material selection for cryogenic wind tunnel models are now receiving attention at a specialist level following discovery of some practical difficulties during model cons' ~uction and use. It seems that there are no fundamental barriers but there is plenty ›i scope for work to improve understanding of the materials and confidence in their use.

Strain gauge balance development is well advanced at NASA Langley and to a lesser extent at one or two places in Europe. However, no one has claimed that the accuracy of axial-force measurement is as high as desirable and it seems likely on fundamental grounds that it will never be so good as in tunnels with a restricted stagnation temperature range because any advances in technique will be applicable to them also. A new balance principle, insensitive to temperature effects, would be a valuable advance but all the effort so far has gone into improving traditional designs.

Optical methods of flow visualization and measurements (including surface flow visualization) seem to be desirable facilities for cryogenic tunnels but applying them in NTF and ETW show all the difficulties which have appeared in existing large tunnels devoted to industrial testing and in addition there are the cryogenic constraints.

Adaptive walls have been fitted to two of the principal small cryogenic tunnels in USA and France and are being actively considered for ETW as a retrofit. This complicates further the problem of designing a wind tunnel test section to provide, or at least preserve, all the desirable options for the future. This matter perhaps falls outside the strict domain of cryogenic test technology but the wind tunnel test section is the arena in which all the various options compete. It seems necessary for some selection to be made amongst the options to reduce the design problems to manageable proportions.

The conclusion of these concluding remarks is that a substantial effort is still required to find solutions to a number of problems of cryogenic test technology. The eventual benefits would arise in the form of greater productivity, reduced costs and/or higher accuracy in the operation of cryogenic wind tunnels. In Europe there is still time for better understanding of certain subjects in cryogenic technology to influence the detail design of ETW.

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tion. The effects on aerodynamic coefficients are linear but small and an order lower than the differences due to un-adapted wall setting. Nevertheless, compared to the effect of Reynolds number, the effect of wall temperature is greater.

A theoretical approach to this question is included in a paper[9(10)] on simulation errors in ETW in which it is said that for wall temperature deviations of less than 10% compared with the adiabatic case the results show no considerable differences for separation behaviour although small systematic deviations in skin friction occur. In particular, the shock boundary-layer interactions do not exhibit a special sensitivity.

Transition fixing. Both the McDonnell Douglas and ONERA/CERT papers referred to above note the necessity for transition fixing and the technical difficulties in doing so without unduly affecting the thin boundary layers and thus the aerodynamic coefficients at high Reynolds numbers. For example, the roughness height employed in the ONERA/CERT tests on the CAST 7 aerofoil mentioned above was 0.03 mm (about 0.001 inch), a size difficult to apply and control accurately.

A fundamental study[9(18)] has been undertaken at ONERA/CERT in a low-speed wind tunnel to discover if a cavity in the airofoil surface, instead of a protuberance, would be as effective and easier to realize. The necessary ratios of length and depth of grooves to displacement thickness are larger than the roughness height ratio which produces the same results. It is suggested that it will be easier to trip a very thin boundary layer by means of a shallow groove than externally-applied roughness. However, although the dimensions of the groove may be more accurately controlled its location would have to be decided at the time of manufacture.

Condensation. The paper on simulation errors referred to above also includes results on calculations of inviscid flows round two-dimensional profiles for conditions which approximate the case of heterogeneous condensation with a large number of condensation nucleii existing in the approaching flow. These results indicate that small amounts of condensate are admissible without affecting the accuracy of the measurements: deviations first become noticeable for drag measurements. The condensation model used in the calculations has been verified up to stagnation pressures of 1 atm by comparison with experimental results obtained by a so-called "stream tube duplication" method. This utilises a test-section in an adapted hypersonic low-density wind tunnel at DFVLR Göttingen (Figure 30) which is more fully described in reference 45. The static pressure and Mach number distribution on the upper surface of an airfoil is simulated on the centre line of a suitably-contoured nozzle over a length of about 100 mm. Condensation was detected by pressure measurements and laser light scattering. Both experiments and calculations indicate a possible supercooling for typical transonic flows of about 18 $\pm$ 4K below the static liquefaction boundary represented by the vapour pressure curve.

CONCLUDING REMARKS

In the process of compiling this report the authors are inevitably reminded of the different situations in USA and Europe concerning cryogenic test technology. In the USA there was an earlier start, only one national establishment (NASA Langley) is involved instead of four in Europe, and that establishment has a more direct commitment and more in-house development effort available. Further, now that NTF (and TCT) are in operation the available NASA effort can be directed towards the supporting technology whereas in Europe the principal interest at present is in designing and building ETW and the most, some say the only, urgent problems of cryogenic technology are those which affect the detail design of the tunnel. The work already done in USA has already had a strong influence on European ideas and programmes but the different approaches to the tunnel design have meant that there are essential differences in cryogenic technology requirements.

No unforeseen difficulties in the operation of cryogenic wind tunnels have been discovered but, compared with most conventional wind tunnels, there will be effects on tunnel operations from various directions (high dynamic pressure, properties of materials at low temperatures, the times taken to change model or tunnel temperatures, the extra complexity of tunnel control). These effects may impose some accuracy limitations but these will be compensated for by decreases in simulation errors in other directions, particularly regarding Reynolds number.

Some of the principal technical problems which remain to be solved are mentioned below.

Model changes and adjustments between runs must either be made at low temperatures or the model must be warmed. The first case presents some difficulty for human operators working with protective clothing and perhaps breathing apparatus. In the second case temperature conditioning the model will take some time in order to limit thermal stresses: moreover, the temperature and thermal gradients in the internal strain gauge balance, if fitted, will require careful attention. There is some argument that remotely-controlled manipulators might ease the problem but this has not yet been demonstrated, it will require an expensive development programme to do so. Further, the complications in the design of the wind tunnel test section would be formidable if not actually unacceptable. Model temperature conditioning before a run or between runs may by partially accomplished outside the test section but it seems likely that final conditioning will have to take place in the tunnel flow if accuracies of the order of 1% are required.

The full capabilities of the new tunnels cannot be exploited without reduced factors of safety in the model design which will require much more attention to stressing and

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14. Abstract

This Advisory Report reviews the status of cryogenic windtunnel test technology and includes the results of several meetings sponsored by the Windtunnel Testing Techniques Committee of the Fluid Dynamics Panel among experts in the subject area.

This report follows AGARD Advisory Report AR-174 on "Windtunnel Capability Related to Test Sections, Cryogenics and Computer-Windtunnel Integration" published April 1982, which reports the results of earlier meetings convened on the subject of Cryogenic Test Technology.

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